The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures

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LONG-TERM GOAL

The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering and transmission in bubbly mixtures pertinent to the shallow water ocean acoustics scenario. This includes a conceptual understanding of the role played by stabilization mechanisms in bubble dynamics and longevity. Of particular interest is the phenomenological delineation of different regimes of behavior.

OBJECTIVES

An objective specific to this project is the extension of the theory of sound transmission in bubbly liquids to derive bubbly-fluid attenuation characteristics for both small amplitude (linear response) and large amplitude (nonlinear response) forcing, ultimately incorporating the effects of contaminating surface-active solutes. A second objective is the development of a unique laboratory capability for the precise and accurate measurement of the frequency-dependent complex acoustic impedance of well-characterized bubble clouds. Cloud characterization implies the precise knowledge of all bubble population statistics, both spatially and size-wise.

APPROACH

All aspects of the work proceed in collaboration with W. Carey of NUWC; this project is the result of a joint planning letter submitted in FY 96. Also involved is BU Prof. G. McDaniel (data analysis and modeling) as well as two BU graduate students. The approach involves a balance between modeling and experiments to predict and measure propagation and scattering characteristics. A core issue is the dynamics of a single bubble for both small and large amplitude forcing. This is handled numerically using either the Keller or Gilmore formulations for bubble dynamics. From this, the attributes of bubble behavior (mainly damping and resonance response) can be quantified and incorporated into a comprehensive description of sound propagation and scattering by extending the Wood-Foldy-Morse theories. The final step is to incorporate the effect of surface active materials by adapting numerical models developed by Church [1995] and Allen [1997].

Laboratory experiments will measure the complex impedance of bubble distributions terminating sound-hard impedance tubes over frequencies ranging from well below to well above bubble resonance

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(of order 5 kHz - 250 kHz). The bubbly medium can be characterized optically using a stereo microscope. The frequency-dependent complex impedance of the termination derives from a measurement of the standing wave ratio for a series of normal modes. From this, the phase velocity and attenuation of the bubbly medium is obtained.

Experiments that focus on nonlinear propagation through bubbly media are planned for the out years. This will involve the use of an annular array (500 kHz) to insonofy a bubbly liquid with short duration, large amplitude tone bursts. Of interest is the evolution from linear to shocked wavefront (and the resulting excess attenuation) as a function of bubble population statistics. Implications related to the formation of nonlinear beams in bubbly media will be addressed.

WORK COMPLETED

During the FY 98 period the experimental apparatus to measure sound speed and attenuation in bubbly liquids was assembled and initial measurements performed. A special transducer design was developed to allow sound generation at the entrance to test apparatus while at the same time mechanically isolating the transducer from the wall of the test tube. This design was shown to minimize the production of a variety of tube wall waves while at the same time producing plane cylindrical waves within the tube. The transducers have been fabricated, tested and calibrated. They feature an integrated head accelerometer and a calibrated acoustic receiver. The final component of the experimental apparatus was the bubble generator. A novel technique for generation of micro-bubble distributions was developed based on the work of Chiba & Takahashi [1998]. This system employs a rotating porous cylinder though which air is forced. By varying the overpressure and the rotational speed (i.e. the tangential flow velocity at the surface of the cylinder), it is possible to vary both the void fraction and the bubble size distribution. Bubbles as small as 15 µm are easily generated, even in fresh water.

During this period the final analysis of the low-frequency bubble scattering data was completed. The results have been documented in a Master's Thesis and a definitive Journal article has been written. This analysis clearly removes all ambiguities and shows a monopole scattering characteristic of a free bubble cloud which agrees with the classical low frequency scattering formulation.

We have also completed a review of the current work on the propagation (scattering) through (from) bubbly liquids and incorporated these results in a general formulation which clearly illustrates the physical acoustics of bubbly liquids for frequencies below, through, and above the bubble resonance frequencies. This treatment is consistent with the Kramers-Kronig treatment and will provide the theoretical underpinnings for our future experiments.

RESULTS

A significant result is the finding agreement between the measured free-field backscatter target strength from a cloud of bubbles driven well below the resonance frequency of the bubbles and classical scattering theory which predicts the monopole backscatter intensity and resonance frequency (see Fig. 1) of the clouds treated as an effective medium. This when coupled to the predication of the radiation of bubble clouds produced in lake and laboratory experiments completes the validation of the theory of low-frequency sound radiation and scattering from bubble clouds.

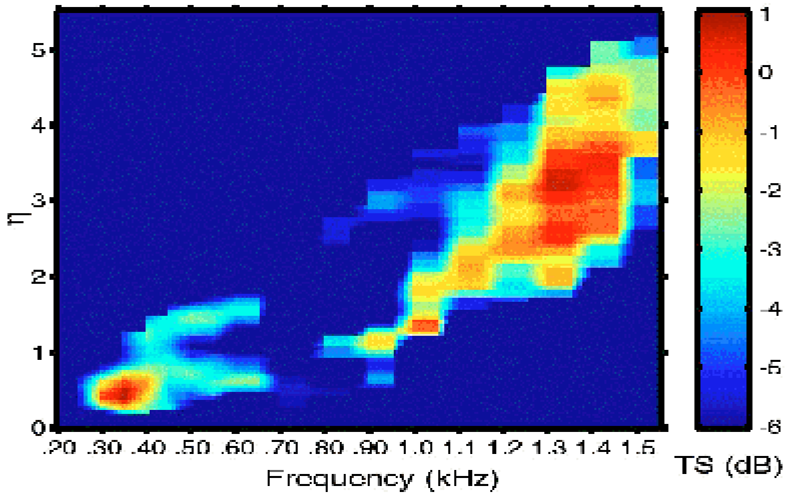

Figure 1. Plot of the measured target strength (TS) for a submerged bubble cloud vs. frequency and distance above the bubble generator (measured in wavelengths). Note the pronounced monopole resonance at 325 Hz. Note also the horizontal bands emanating from this scattering peak, indicative of multipath interference between the sound scattered from the cloud and the bubbler. This interference has been modeled, and the resulting bias subtracted from the measured TS. The result is quantitative agreement between theory and experiment.

The sound-hard tube apparatus and on-line measurement instrumentation necessary for this investigation has been completed and has been used in a series of test to verify our assumptions and to measure classical results. Our student has measured the modal patterns in a bubbly filled tube, Fig. 2, as well as the modal amplitude functions. These are consistent with the predictions of our low frequency formulation and were used as part of an educational demonstration lecture at the Norfolk ASA meeting.

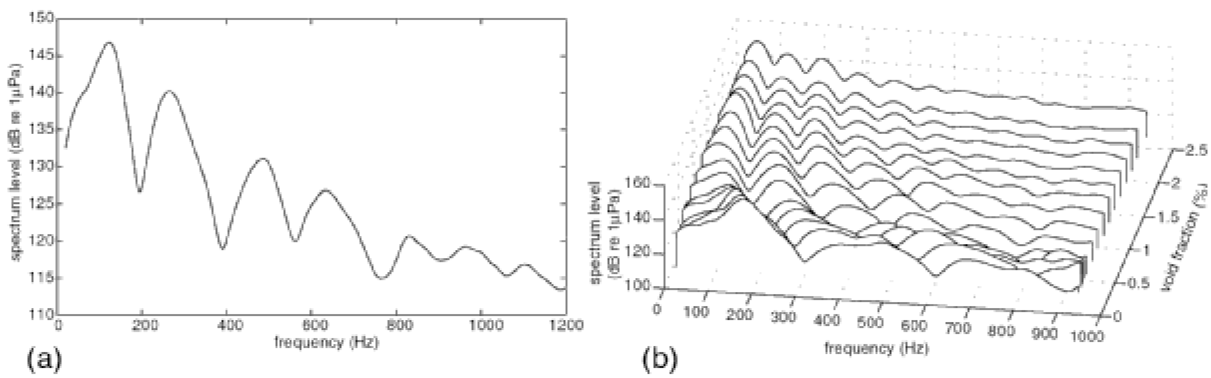

Figure 2. (a) Spectral content of bubble-generated sound in a cylindrical tube (0.5-m length, 5.08-cm inner diameter), for 0.4% void fraction. (b) Waterfall plot showing variation of spectral content for a range of void fractions; note the uniform shift to lower eigenfrequencies as the void fraction is increased. The sound source is provided by the bubbles pinching off the hypodermic needles positioned at the bottom end of the tube.

IMPACT/APPLICATIONS

The notion that bubbles can be driven to pulsate collective is important to any assessment of scattering and attenuation from oceanic bubble clouds and layers. The area of research is important to HF/SW noise and propagation, SW mine hunting sonars, high power acoustic arrays for MCM, and wake homing torpedoes. Furthermore, the acoustical measurement of bubble populations and circulation patterns may depend on the physics of multiple scattering and absorption in bubbly mixtures

RELATED PROJECTS

1 - A collaboration with NUWC/Newport (R. Costa) and CSS/Panama City (K. Commander) on an instrument designed for *in situ* measurement of oceanic bubble dissolution rates. The instrument was successfully deployed as part of a wake physics sea test at Nanoose in September, 1998.

2 - A collaboration with APL/UW (S. Kargl) on the physics of nonlinear beam forming. The issues of bubble-mediated enhanced nonlinearity and dissipation in bubbly water are key to both projects. The goal of the beam forming project is to assess the viability of high-intensity sound beams for MCM.

3 - A collaboration with Univ. Virginia (J. Allen) on developing new theories that describe the dynamics of bubbles in viscoelastic media. The PI was the research advisor for J. Allen, a UW Ph.D. student in Mechanical Engineering who completed his dissertation September ‘97.

REFERENCES

C.C. Church, J. Acoust. Soc. Am. **97**, 1510-21 (1995).

J. Allen, Ph.D. Dissertation, Dept. of Mechanical Engineering, Univ. of Washington (1997).

N. Chiba and Y. Takahashi, “Generation of micro air bubbles of uniform size in water,” Proceedings of the 3rd International Symposium on Cavitation, Grenoble, France, pp. 91-94 (1998).

PUBLICATIONS

W.M. Carey and R.A. Roy, ìThe low frequency radiation and scattering of sound from bubble distributions near the sea surface,î in Proceedings of the 16th International Congress on Acoustics and the 135th Meeting of the Acoustical Society of America, Vol. IV, pp. 3035-3036 (1998).

J. Allen and R.A. Roy, ìBubble dynamics in non-Newtonian fluids,î in Proceedings of the 16th International Congress on Acoustics and the 135th Meeting of the Acoustical Society of America, Vol. IV, pp. 2283-2284 (1998).

R. Costa, R.A. Roy, K.W. Commander, V.B. Johnson, and A.C. Colbert, ìA novel approach for obtaining bubble dissolution measurements at sea,î in Proceedings of the 16th International Congress on Acoustics and the 135th Meeting of the Acoustical Society of America, Vol. II, pp. 711-712 (1998).

L.A. Crum, R.A. Roy, H.C. Pumphrey and A.P. Prosperetti, “The underwater sounds produced by impacting snowflakes,” J. Acoust. Soc. Am., submitted August 1998.

Related Publications

P. Edson, R.A. Roy, and S.G. Kargl, ìNonlinear wave propagation from a discrete annular array: experiments,î in Proceedings of the 16th International Congress on Acoustics and the 135th Meeting of the Acoustical Society of America, Vol. I, pp. 533-534 (1998).

S.G. Kargl, R.A. Roy, and P. Edson, ìNonlinear wave propagation from a discrete annular array: theory,î Proceedings of the 16th International Congress on Acoustics and the 135th Meeting of the Acoustical Society of America, Vol. I, pp. 531-532 (1998).

R. Evans and W. Carey, " Frequency dependence of sediment attenuation in two low-frequency shallow-water acoustic experimental data sets," J. Oceanic Eng. **23**(4), 439-447 (1998).

S. Rajan, J. Doutt, and W. Carey, " Inversion for the compressional wave speed profile of the bottom from synthetic aperture experiments conducted in the Hudson Canyon area," J. Oceanic Eng. **23**(3), 174-187 (1998).

W. Carey, "Sonar array characterization: Experimental results," J. Oceanic Eng. **23**(4), 297-306 (1998).

W. Carey, " The determination of signal coherence length based on signal coherence and gain measurements in deep and shallow water," J. Acoust. Soc. Am. **104**(2), 831-837 (1998).

W. Carey, J. Reese, and H. Bucker, "Environmental acoustic influences on array beam response," J. Acoust. Soc. Am. **104**(1), 133-140 (1998).

W. Carey, J. Reese, and C. Stuart, " Mid-frequency measurements of array signal and noise characteristics," J. Oceanic Eng. **22**(3), 548-565 (1997).